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(54) **ELECTRICAL ENERGY CONVERTER AND ASSOCIATED SYSTEM FOR CONVERTING ELECTRICAL ENERGY**

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See application file for complete search history.

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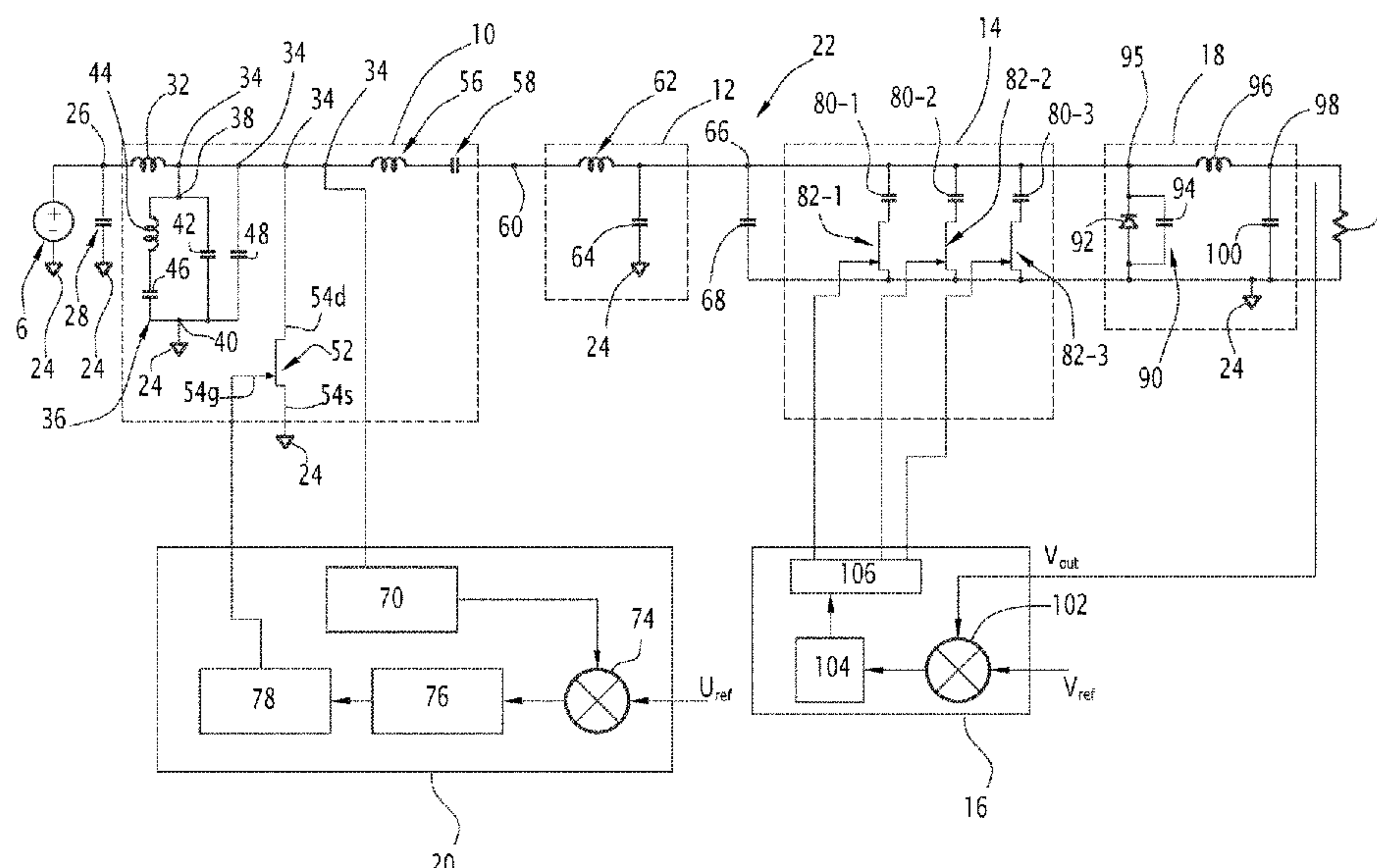
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(57) **ABSTRACT**

The invention relates to an electrical energy converter including an inverter (10) for obtaining alternative electrical energy from a DC electrical energy source. The inverter includes a switch (52) having first and second conduction terminals for receiving an AC voltage, the electrical energy converter being suitable for supplying an output electrical energy to a load (8). Said converter includes a capacitive circuit (14) with variable and controllable capacitance, connected between the inverter (10) and the load (8), the control of a modification of said capacitance making it possible to obtain a modification of an electrical output parameter of the converter. The associated system for converting electrical energy includes such an electrical energy converter and a control module (16) configured for receiving as input a setpoint value of said output electrical parameter ( $V_{ref}$ ) of the converter and for controlling the variable capacitance of said capacitive circuit (14) as a function of said setpoint value.

**10 Claims, 5 Drawing Sheets**



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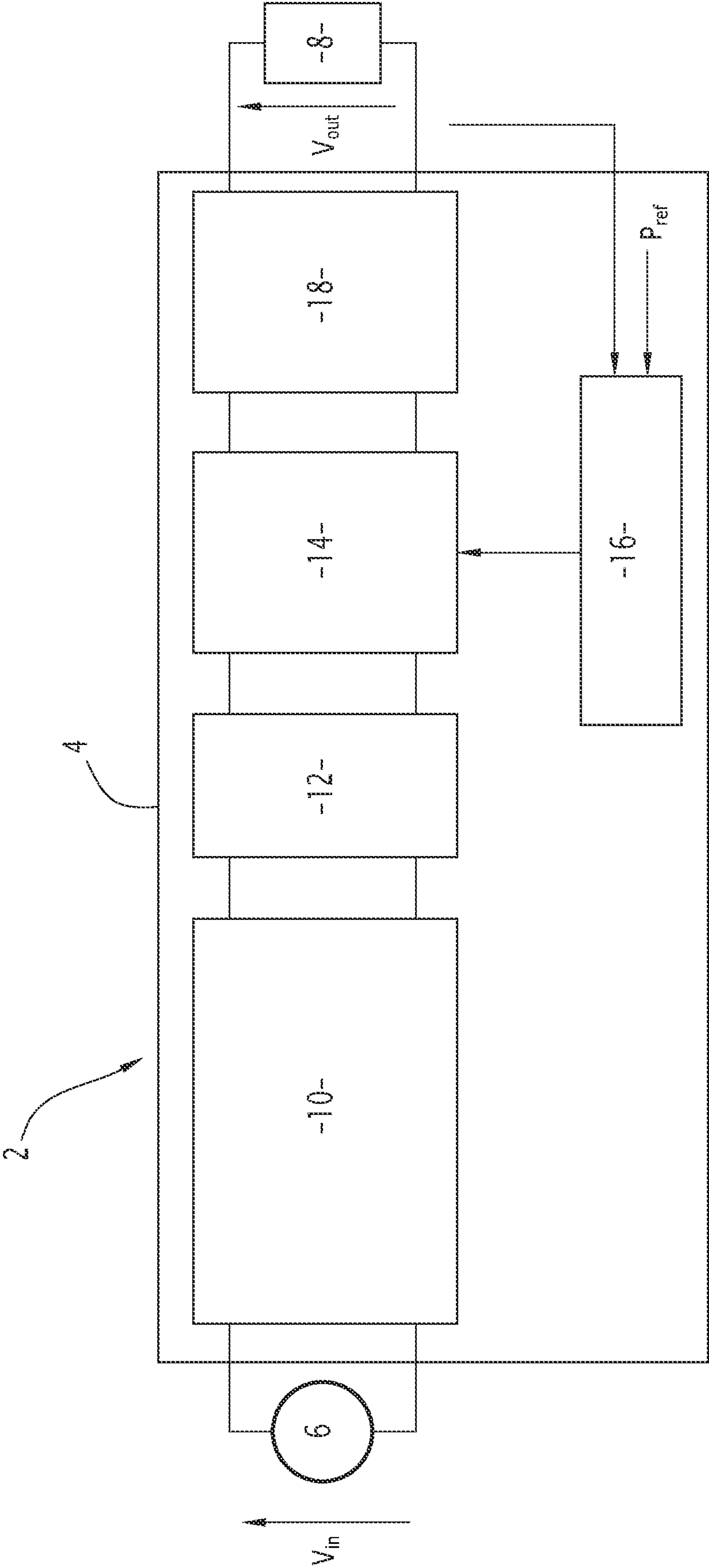


FIG.1

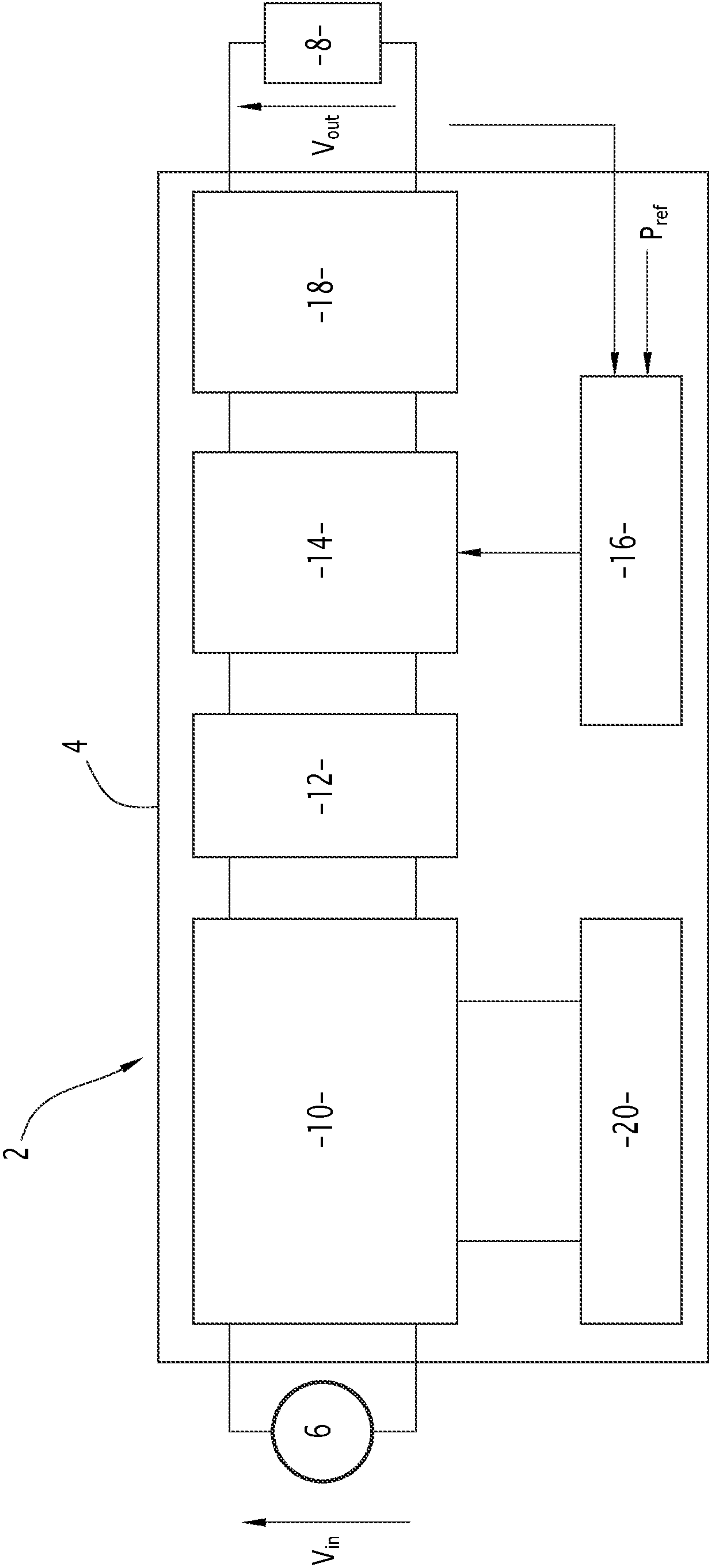


FIG. 2



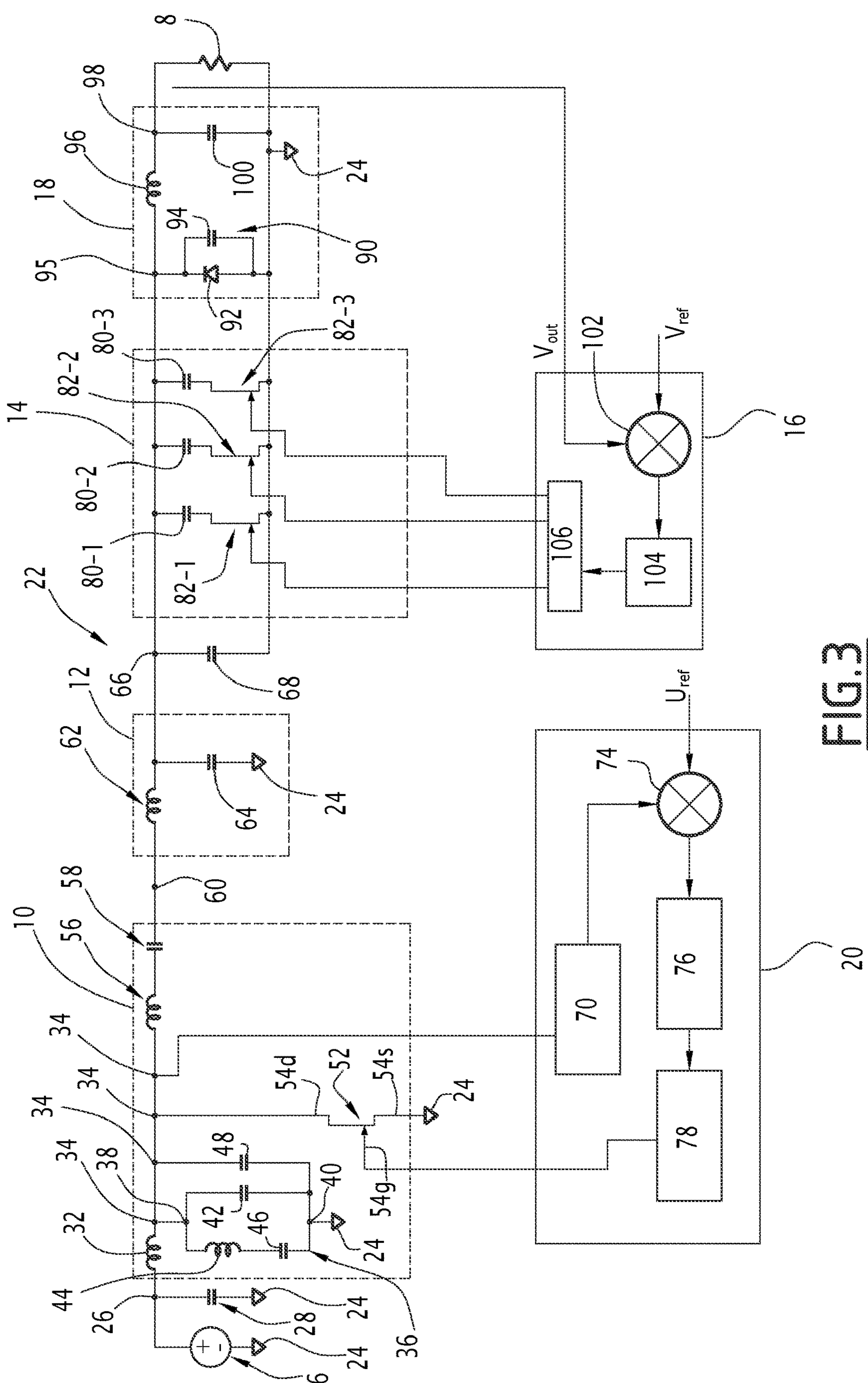


FIG. 3

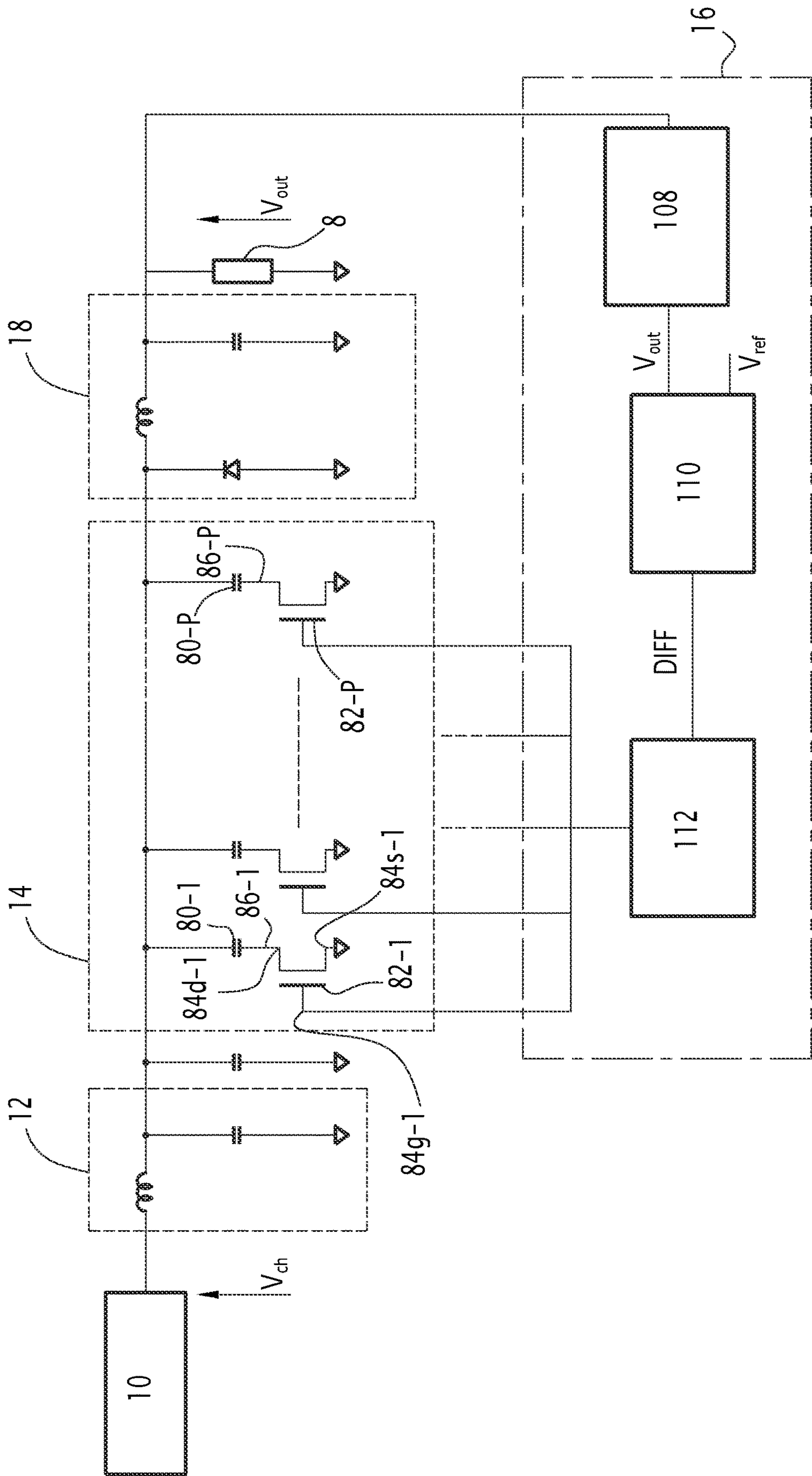


FIG.4

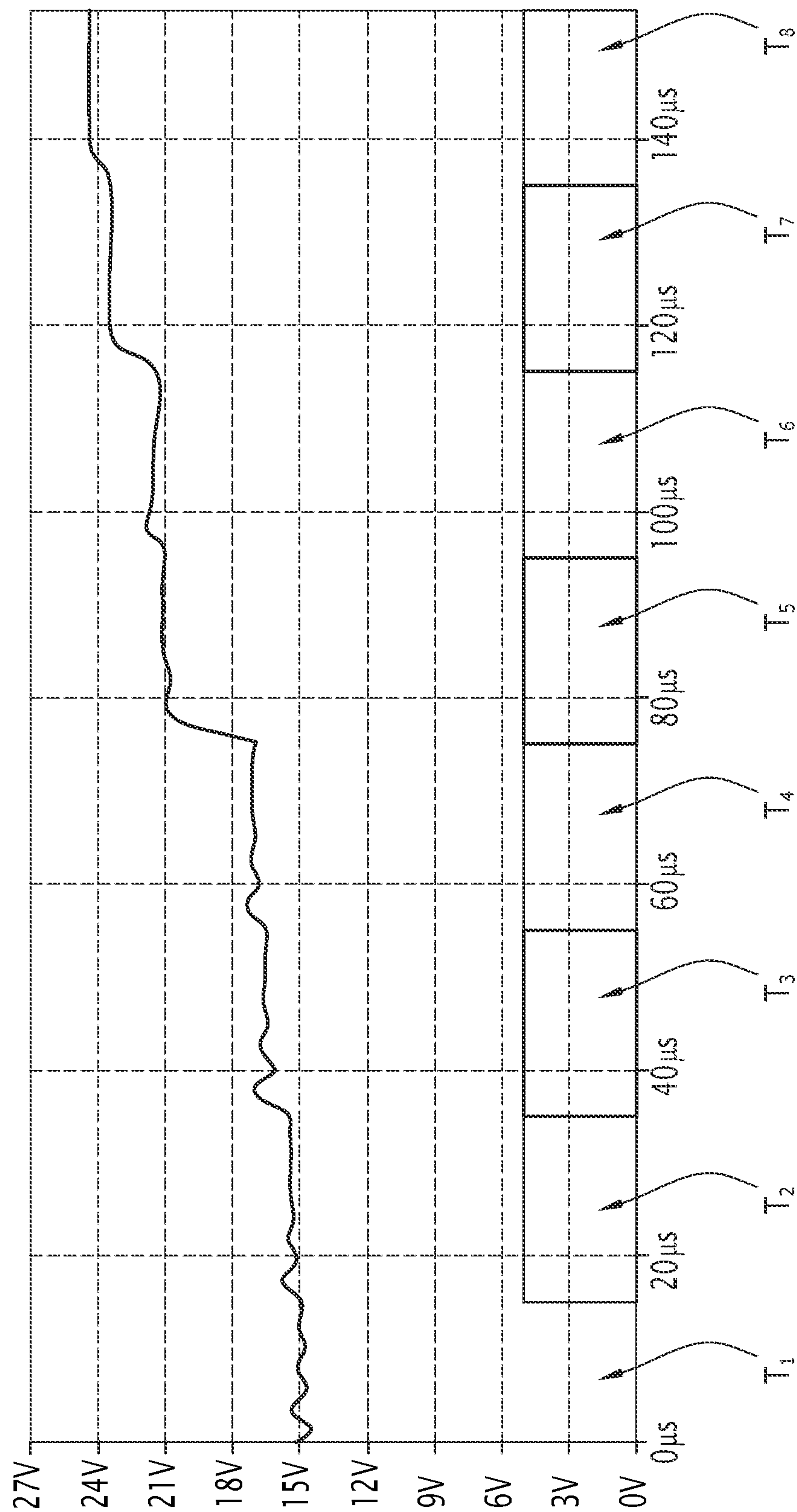


FIG.5



# ELECTRICAL ENERGY CONVERTER AND ASSOCIATED SYSTEM FOR CONVERTING ELECTRICAL ENERGY

This application claims priority to French Patent Application No. 22 04188 filed May 3 2022, the entire disclosure of which is incorporated by reference herein.

## FIELD OF THE INVENTION

The present invention relates to an electrical energy converter and an associated system for converting electrical energy.

The invention belongs generally to the field of electrical devices, and more particularly electrical energy converters such as a power converter.

The invention applies more particularly to power converters suitable for working at high frequencies (2 MHz to 30 MHz) and very high frequencies (30 MHz to 300 MHz).

## BACKGROUND OF THE INVENTION

In particular, electrical energy converters known as "Direct Current-Alternative Current" (DC-AC), also called inverters, suitable for working at high and very high frequencies (30 MHz to 300 MHz) are known.

Electrical energy converters known as "Direct Current-Direct Current" (DC-DC) are also known, e.g. integrating an inverter of the type described above and an Alternative Current-Direct Current (AC-DC) converter, also known as a rectifier.

More particularly, there are a plurality of classes of electrical energy converters including a switch, typically a transistor, including first and second conduction terminals intended for receiving an alternative voltage.

Such an electrical energy converter is intended for supplying a load with real or complex impedance. For the converter to work properly, it is necessary to switch off the transistor at zero voltage (in English, "zero voltage switch"), i.e. when the alternative voltage at the terminals of the transistor is substantially equal to zero. By substantially equal is meant herein to within 10%, preferentially to within 5%.

Conventionally, the components of the converter and the control duty cycle of the transistor are adjusted for closing the transistor at zero voltage, for a given load impedance. In such case, any modification of the impedance of the load, after adjustment, carries a risk of inducing a degraded efficiency of electrical energy conversion.

Patent application FR 2106069 filed on 9 Jun. 2021 proposes a power converter including a switching regulation unit for automatically regulating the control duty ratio of the transistor, and thus for automatically adapting to a modification of the load impedance while ensuring a switching at zero voltage.

However, the power converter described in patent application FR 2106069 is suitable for working for an output voltage amplitude and an output power which are substantially fixed.

More generally, known power converters are configured for working at fixed output voltage or power, for a load to be supplied with a variable or a fixed impedance.

The subject matter of the present invention is to overcome such drawback by proposing an electrical energy converter, an electrical output parameter of which, and in particular the amplitude of the output voltage, can be regulated within a regulation range.

## SUMMARY OF THE INVENTION

To this end, the invention proposes, according to one aspect, an electrical energy converter including an inverter for obtaining an alternative electrical energy from a DC electrical energy source, said inverter including a switch including first and second conduction terminals intended for receiving an alternative voltage, the electrical energy converter being suitable for supplying an output electrical energy to a load having a load impedance. Such converter includes a capacitive circuit with variable and controllable capacitance, connected between the inverter and the load, the control of the modification of said capacitance making it possible to obtain a modification of an electrical output parameter of the converter.

Advantageously, the electrical energy converter according to the invention includes a capacitive circuit with variable, controllable capacitance, which can be used for regulating, upon control, the regulation of an electrical output parameter of the converter.

The electrical energy converter according to the invention can further have one or a plurality of the features below, taken independently or according to all technically feasible combinations.

The output parameter is an output voltage or current or power of the converter.

The converter includes an impedance matching unit configured for matching an output impedance of said inverter to the load impedance, said variable capacitance capacitive circuit being connected between the impedance matching unit and the load to be supplied.

The converter further includes a rectifier unit for obtaining a DC electrical power from an alternative electrical power source, said rectifier unit being connected between the capacitive circuit with variable capacitance and the load to be supplied.

The converter further includes a regulation unit configured for switching the switch when the voltage between said first and second conduction terminals of said switch is substantially zero.

The capacitive circuit includes a plurality of capacitors arranged in parallel, each capacitor being connected in series with an associated switch, said capacitor being connected to the capacitive circuit when the associated switch is in the closed position, said capacitor being disconnected from the capacitive circuit when the associated switch is in the open position, the variable capacitance of said capacitive circuit being equal, at a given instant, to the sum of the capacitances of the capacitors connected in the capacitive circuit at said given instant.

A first of said capacitors has an initial capacitance, the other capacitors each having a capacitance which is a multiple of said initial capacitance.

According to another aspect, the subject matter of the invention is a system for converting electrical energy including an electrical energy converter as briefly described hereinabove and an electronic module for controlling the capacitive circuit with variable capacitance, configured for receiving as input, a setpoint value of said electrical output parameter of the converter and for controlling the variable capacitance of said capacitive circuit as a function of said setpoint value.

According to a variant, the control module includes a subtractor, configured for receiving, on a first input, a value of said electrical output parameter of the converter, and for receiving, on a second input, the setpoint value of said electrical parameter, the subtractor being configured for



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calculating a difference between the value of the output electrical parameter of the converter and the setpoint value.

According to one variant, the control module further includes a conversion module configured for converting the computed difference into a control signal for the capacitive circuit.

### BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the invention will be clear from the description thereof which is given below as a non-limiting example, with reference to the enclosed figures, among which:

FIG. 1 is a schematic view of a system including an electrical energy converter according to a first embodiment;

FIG. 2 is a schematic view of a system including an electrical energy converter according to a second embodiment;

FIG. 3 schematically shows an embodiment of an electrical conversion system according to FIG. 2;

FIG. 4 shows, schematically and partially, a second embodiment of a control module of an electrical energy converter;

FIG. 5 is a graph representing an example of the change of the output voltage of an electrical energy converter including a capacitive circuit according to the invention.

### DETAILED DESCRIPTION OF EMBODIMENTS

Hereinafter in the description, the term “substantially equal to” defines a relation of equality within plus or minus 10%, preferentially within plus or minus 5%.

FIG. 1 diagrammatically shows a system for converting electrical energy 2, including an electrical energy converter 4.

The electrical energy converter 4 is preferentially a DC-DC converter. In such case, the converter 4 includes a rectifier, as described in greater detail hereinafter.

The system 2 includes a source of electrical power 6, supplying a substantially DC voltage  $V_{in}$ . The power source 6 is e.g. a battery or a solar panel.

The electrical energy converter 4 is then configured for raising the value of the DC voltage between the input thereof and the output thereof and is then also called a step-up DC-DC converter; or is configured for lowering the value of the DC voltage between the input thereof and the output thereof and is then called a step-down DC-DC converter.

The electrical power converter 4 is configured for delivering N distinct output voltage(s) from E distinct input voltage(s), E and N each being an integer greater than or equal to 1.

In the examples shown in FIG. 1, the electrical energy converter 4 is configured for delivering an output voltage denoted by  $V_{out}$  from an input voltage denoted by  $V_{in}$ , the number E of input voltage(s) and the number N of output voltage(s) being then each equal to 1.

The electrical energy converter 4 is connected to a load 8 with either a real or a complex load impedance.

In a variant (not shown), the electrical energy converter 4 is configured for delivering a plurality of distinct output voltages from one or a plurality of distinct input voltages, the number N of distinct output voltages being then greater than 1.

In a further variant, the electrical energy converter 4 is configured for delivering one or a plurality of distinct output

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voltages from a plurality of distinct input voltages, the number E of distinct input voltages then being greater than 1.

In a further variant, the electrical energy converter 4 is configured for delivering a plurality of distinct output voltages from a plurality of distinct input voltages, the numbers E and N being then each greater than 1.

When the electrical energy converter 4 is configured for delivering a plurality of distinct output voltages, the converter 4 is typically connected to a plurality of loads 8.

The electric power converter 4 includes a direct current-alternative current (DC/AC) converter unit 10, also known as an inverter.

The inverter 10 is preferentially a single-switch inverter, the switch being e.g. a transistor, suitable for working at high frequency (HF) and very high frequency (VHF), typically in a frequency range from 2 MHz to 300 MHz. In such case, the electric power converter 4 is a VHF converter.

The transistor is e.g. an insulated gate field effect transistor, also called MOSFET (Metal Oxide Semiconductor Field Effect Transistor). In a variant, the transistor is a bipolar transistor; an insulated gate bipolar transistor, also called IGBT (Insulated Gate Bipolar Transistor); a silicon (Si) transistor, a GaN (Gallium Nitride) transistor; a silicon carbide (SiC) transistor, a diamond transistor, or a thyristor.

The inverter 10 is e.g. of the type including a piezoelectric element.

More generally, the electrical energy converter 4 works in a similar way with a plurality of inverter topologies, e.g. Class E, Class Phi2, Class L-piezo inverters.

For example, class E is defined in the article by N. O. Sokal and A. D. Sokal, “Class E-A new class of high-efficiency tuned single-ended switching power amplifiers,” published in *IEEE Journal of Solid-State circuits*, Vol. 10, no. 3, pp. 168-176, June 1975; the Phi2 class is defined in the article by J. M. Rivas, Y. Han, O. Leitermann, A. Sagneri and D. J. Perreault, “A High-Frequency Resonant Inverter Topology with Low Voltage stress,” published in 2007 *IEEE Power Electronics Specialists Conference*, 2007, pp. 2705-2717; the L-piezo class is defined in the article by V. Massavie, G. Despesse, S. Carcouet and X. Maynard, “A new topology of resonant inverter including a piezoelectric component,” published in 2021 *23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*, 2021, pp. 1-10.

The electrical energy converter 4 further includes, in the embodiment illustrated, an impedance matching unit 12, which is configured for matching the impedance of the load 8 and the output impedance of the inverter 10.

For example, the impedance matching unit 12 is a circuit including real or complex passive components. A plurality of impedance matching circuit topologies are known, e.g. an L-shaped topology including inductive and capacitive components, arranged so as to achieve low-pass or high-pass filtering; a pi-shaped topology or a T-shaped topology.

FIG. 3, described in greater detail hereinafter, illustrates a particular embodiment in which the impedance matching unit is formed by an inductive element, e.g. a coil, and a capacitor (LC circuit), with low-pass L-shaped topology.

Moreover, the electrical energy converter 4 includes a capacitive circuit 14 with variable capacitance, the variation in capacitance being controllable by a control module 16, advantageously used for varying an electrical output parameter of the electrical energy converter by varying the capacitance of the capacitive circuit 14. The electrical output parameter of the electrical energy converter 4 is e.g. a voltage, a current or a power.



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The capacitive circuit **14** with variable capacitance is connected between the impedance matching unit **12** and the load **8**.

When the electrical energy converter **4** is configured for delivering a plurality of distinct output voltages for supplying a plurality of loads **8**, the converter **4** includes a capacitive circuit **14** with variable capacitance for each load **8**.

In the embodiment illustrated, the capacitive circuit **14** is connected between the impedance matching unit **12** and a rectifier unit **18**, being also a part of the electrical energy converter **4**, in the case where the electrical energy converter **4** is a DC-DC converter.

The variation of the electrical output parameter is achieved by applying to the input of the control module **16** a setpoint value  $P_{ref}$  of the electrical parameter value, e.g. a voltage setpoint value  $V_{ref}$ , or a current setpoint value  $I_{ref}$ , or a power setpoint value  $P_{ref}$ .

In another embodiment, illustrated in FIG. 2, the system for converting electrical energy **2** includes a converter **4**, which includes, in addition to the elements described hereinabove which are referenced by the same numbers, a regulation unit **20**, which is configured for providing a switching at a substantially zero voltage ZVS (zero voltage switch) of the switch (e.g. transistor) of the inverter **10**.

Indeed, advantageously, switching at substantially zero voltage leads to little disturbance of the inverter **10** and generates low energy losses at the inverter switch.

For example, in one embodiment, the regulation unit is of the type described in patent application FR2106069, configured for performing a switching at substantially zero voltage (ZVS).

FIG. 3 illustrates an example of a system for converting electrical energy **22**, the elements of which are described in detail hereinafter.

In said particular example, the regulated output electrical parameter is the voltage.

The system for converting electrical energy **22** includes a source of electrical energy **6**, supplying a substantially DC voltage  $V_{in}$ , including a negative terminal (denoted  $-$ ) connected to a node **24**. The node **24** is a node for applying a reference potential, e.g. the chassis ground. The power source **6** further includes a positive terminal (denoted  $+$ ), connected to an input node **26** of the inverter **10**.

The node **26** is also connected to one terminal of an optional capacitor **28** of given capacitance  $C_{in}$ , which smooths the input voltage, the other terminal of the capacitor **28** being connected to a node **24** for applying the reference potential.

The assembly formed by the source of energy referenced by **6** and the capacitor **28** forms, in the embodiment illustrated, a source of electrical energy.

In the embodiment illustrated in FIG. 3, the inverter **10** is an L-piezo inverter.

The inverter **10** includes an inductive element, e.g. a coil **32**, one terminal of the coil **32** being connected to the input node **26** of the inverter, the other terminal being connected to a node **34**.

The piezoelectric element **36** is connected between the node **34** and a node **24** for applying the reference potential.

In the embodiment illustrated, the piezoelectric element **36** is modeled in the form of two branches connected in parallel between two terminals (or electrodes) **38** and **40**, the terminal **38** being connected to the node **34** and the terminal **40** being connected to the node **24**, one of the branches including a capacitor **42**, the other branch, called resonant

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branch, including an LC circuit formed by an inductive element, e.g. a coil **44**, connected in series with a capacitor **46**.

The term branch refers to a part of an electrical circuit located between two consecutive nodes, the elements of a branch being connected in series.

The capacitance of the capacitor **42** connected in parallel with the resonant branch is called parallel capacitance, or blocked capacitance, or reference capacitance, and denoted by  $C_0$ . The voltage across the piezoelectric element **36** then typically corresponds to the voltage across the capacitor **42**.

The inverter **10** optionally includes a capacitor **48** of capacitance  $C_r$ , one terminal of the capacitor **48** being connected to the node **34**, the other terminal of the capacitor **48** being connected to the node **24** for applying the reference potential. The capacitance  $C_r$  is a so-called adjustment capacitance.

The switch **52** is e.g. a field effect transistor (FET), e.g. a MOSFET (Metal Oxide Semiconductor Field effect Transistor).

In a variant, the transistor is a bipolar transistor; an insulated gate bipolar transistor (IGBT); a silicon (Si) transistor, a Gallium Nitride (GaN) transistor; a silicon carbide (SiC) transistor, a diamond transistor, or yet a thyristor.

According to another variant, the transistor is a high electron mobility transistor (HEMT) e.g. based on gallium nitride GaN.

The switch **52** includes a first conduction terminal **54d** (drain), connected to the node **34**, a second conduction terminal **54s** (source) connected to the node **24** for applying the reference potential, and a third control terminal **54g** (gate).

The effect of the control voltage  $V_{gs}$  is to control the switching of the switch **52** between a closed (or on) state and an open (or off) state. When the voltage  $V_{gs}$  is greater than or equal to a threshold voltage, the switch **52** is in the on-state, and when the voltage  $V_{gs}$  is less than the threshold voltage, the switch **52** is in the off-state.

As an example, the switch **52** of the inverter **10** has a switching frequency comprised between 2 MHz and 300 MHz.

The control voltage  $V_{gs}$  is supplied by the regulation unit **20**, with the aim of ensuring a switching of the closing of the switch **52** when the voltage  $V_{ds}$  between the first terminal **54d** (the node **34**, respectively) and the second terminal **54s** of the switch is substantially zero.

The inverter **10** further includes another inductive element **56** e.g. a coil of inductance  $L_s$ , in series with a capacitor **58**, of capacitance  $C_s$ , between the node **34** and an output terminal **60** of the inverter.

A sinusoidal voltage  $V_{ch}$  is obtained at the output of the inverter **10**.

The impedance matching unit **12** includes, in the embodiment of FIG. 3, an inductive element, e.g. a coil **62** of inductance  $L_a$ , connected between the output terminal **60** of the inverter and an output terminal **66** of the impedance matching unit, and a capacitor **64** of capacitance  $C_a$ , connected to the terminal **66** and the node **24** for applying the reference potential.

Thus, in said embodiment, the impedance matching unit has an L-shaped topology.

The electrical energy converter **22** further includes a regulation unit **20** which includes, in said embodiment, a unit **70** for detecting a minimum value of the voltage  $V_{ds}$  and for averaging the voltage over a plurality of alternations, used for obtaining an average  $V_{\alpha}$ . The unit **70** is connected



between the node **34**, connected to the terminal **54d** of the switch **52**, and an input of a subtractor **74**.

The subtractor **74** includes a first input (+) connected to the unit **70** and a second input (−) receiving a reference potential  $U_{ref}$ . The subtractor **74** makes a difference between the first and the second input.

Thus, the subtractor **74** compares the mean voltage  $V\alpha$  with the reference potential  $U_{ref}$ , the reference potential being adjusted so as to obtain a quasi-ZVS operation.

An image signal of a difference between  $V\alpha$  and  $U_{ref}$  is supplied at the output of the subtractor.

The output of the subtractor **74** is connected to the input of a corrector **76**, the corrector **76** being, in one embodiment, an integral proportional corrector. The corrector **76** is used for obtaining a regulation loop which is more stable than if the circuit **20** had no corrector.

The output of the corrector **76** is supplied at the input of a pulse width modulation (PWM) circuit **78**, which is connected to the gate of the transistor **52** so as to supply the voltage control signal  $V_{gs}$ , which controls the switching of the transistor **52**. Thus, the instants of turning-on and turning-off the transistor **52** are controlled by the signal coming from the PWM circuit **78** which is controlled by the corrector **76** which supplies a DC voltage image of a duty cycle to be applied. Such signal is commonly referred to as a “duty cycle”.

In the embodiment shown in FIG. 3, the converter **22** further includes, at the output of the impedance matching unit **12**, a capacitor **68** connected between the output terminal **66** and the node **24** for applying the reference potential, of predetermined capacitance (fixed capacitance), as well as a capacitive circuit **14** with variable capacitance, controlled by a control module **16**.

In the embodiment shown in FIG. 3, the capacitive circuit **14** includes  $P=3$  capacitive components, e.g. capacitors **80-1**, **80-2** and **80-3** connected in parallel, with respective capacitances  $Cvar\_1$ ,  $Cvar\_2$ ,  $Cvar\_3$ .

The number  $P$  of capacitors in the capacitive circuit is a chosen integer.

Each of the capacitors is connected to an associated switch **82-1**, **82-2**, **82-3**, e.g. a transistor.

More generally, **80- $i$**  refers to any of the capacitors of the capacitive circuit, and **82- $i$**  refers to the associated switch.

It is to be noted that a capacitor **80- $i$**  may consist of any association, in series and/or in parallel, of elementary capacitors. The above can be useful for obtaining accurate capacitance ratios between 2 capacitances **80- $i$** . E.g., to obtain a capacitance **80-3** equal to 2 times the capacitance **80-2** which is equal to twice the capacitance **80-1**, it is possible to use the same capacitance reference and to use 2 in parallel for **80-3**, only one for **80-2** and two in series for **80-1**. Thus, using the same reference, the characteristics and temperature drifts will be similar.

The variable capacitance  $Cvar$  of the capacitive circuit **14** is, at a given instant, equal to the sum of the capacitances of the capacitors connected in the capacitive circuit **14**.

A capacitor **80- $i$**  is connected in the capacitive circuit **14** when the switch **82- $i$**  to which same is connected, also called associated switch, is closed, which lets the electric current flow. When the associated switch is open, the capacitor **80- $i$**  is disconnected, and the capacitance  $Cvar\_i$  thereof does not contribute to the total capacitance of the capacitive circuit.

Thus, by controlling the opening and the closing of the switches associated with the capacitors, and consequently by connecting and disconnecting the associated capacitors in the capacitive circuit, it is possible to vary the capacitance  $Cvar$  of the capacitive circuit.

In the illustrated embodiment, it is possible to connect/disconnect each capacitor individually, by applying a control signal to the gate of the associated transistor. Thus, all the combinations of opening/closing of the transistors are conceivable, which can be used for reaching a set of capacitance values  $Cvar$ .

For example, when the capacitive circuit includes 3 capacitors, 8 combinations are conceivable.

In one embodiment, the capacitors **80-1** to **80- $P$**  (where  $P=3$  in the example shown in FIG. 3) have different capacitance values, e.g. increasing and according to a geometric progression (or geometric sequence) of the ratio  $R$ , e.g.  $R=2$ .

As an example, but not limited to,  $Cvar\_1=C$ ,  $Cvar\_2=2C$ ,  $Cvar\_3=4C$ , and more generally  $Cvar\_p=2^{p-1}C$ . E.g., the capacitance value  $C$ , called initial capacitance, is equal to 120 pF.

In the case where the capacitive circuit includes  $P$  capacitors in parallel, with capacitances of increasing values with values  $C$ ,  $2C$ ,  $4C$ , . . . ,  $2^{P-1}C$ , the control of the associated switches can be used for obtaining total capacitance values  $Cvar$  (variable capacitance of the capacitive circuit) ranging from 0 to  $Cvar\_max=(2^P-1)C$ .

In such case, the number of steps of capacitance values is  $2^P$ .

Thereby, the total capacitance  $Cvar$  is written mathematically in the form:

$$Cvar = \sum_{i=1}^P K_i Cvar\_i$$

Where  $K_i$  represents the state of the switch associated with the capacitor of capacitance  $Cvar\_i$ ,  $K_i=0$  if the switch is open, and  $K_i=1$  if the switch is closed.

As indicated hereinabove, in one embodiment, the switches **82-1** to **82- $P$**  are transistors.

E.g., each switch **82- $i$**  is a field effect transistor (FET), e.g. a MOSFET (Metal Oxide Semiconductor Field Effect Transistor).

In a variant, the transistor is a bipolar transistor; an insulated gate bipolar transistor (IGBT), a silicon (Si) transistor, a gallium nitride (GaN) transistor; a silicon carbide (SiC) transistor, a diamond transistor, or a thyristor.

According to another variant, the transistor is a high electron mobility transistor (HEMT) e.g. based on gallium nitride GaN.

Each transistor **82- $i$**  includes a first conduction terminal **84d- $i$**  (drain) connected to a node **86- $i$** , a second conduction terminal **84s- $i$**  (source) connected to the node **24** for applying the reference potential, and a third control terminal **84g- $i$**  (gate).

The control voltage  $V_{gs-i}$  (gate source voltage between the third terminal and the second terminal) has the effect of controlling the switching of the transistor **82- $i$**  between an on-state and an off-state. When the voltage  $V_{gs-i}$  is greater than or equal to a threshold voltage of the transistor, the transistor **82- $i$**  is in the on-state, and when the voltage  $V_{gs-i}$  is less than the threshold voltage, the transistor **82- $i$**  is in the off-state.

Two embodiments of the control module **16** for controlling the respective switching control voltages of the transistors **82-1** to **82- $P$**  will be described hereinafter.

In the embodiment shown in FIG. 3, the converter **22** further includes a class E rectifier **18** the function of which is to rectify the sinusoidal voltage supplied by the inverter **10** in order to obtain a DC output voltage.



In said embodiment, the rectifier unit **18** includes a unit **90** including a diode **92** connected in parallel with a capacitor **94**, the unit **90** being connected between an input node **95** of the rectifier and the node **24** for applying the reference potential, an inductive element, e.g. a coil **96** connected between the node **95** and an output node **98** of the rectifier **18**, and a capacitor **100**, which is an output capacitor of capacitance  $C_{out}$  connected between the node **98** and the node **24** for applying the reference potential.

The output voltage is supplied to a load **8**.

An image of the output voltage  $V_{out}$  is supplied at the input of the control module **16** of the capacitive circuit with variable capacitance.

In one embodiment, the module **16** includes a subtractor **102** which includes a first input (+) on which the output voltage  $V_{out}$  is received and a second input (-) on which a reference voltage  $V_{ref}$  is supplied.

In other embodiments, another electrical parameter is regulated at the output, and a setpoint value of the regulated electrical parameter is provided.

The regulated electrical parameter is e.g. the current, and an output current value is supplied to the first input of the subtractor **102**, and a setpoint value for the current is supplied to the second input of the subtractor **102**.

According to a variant, the regulated parameter is the power, an output voltage value and an output current value are obtained and multiplied so as to obtain an output power value supplied to the first input of the subtractor **102**, and a reference power value  $P_{ref}$  is supplied to the second input of the subtractor **102**.

In the embodiment shown in FIG. **3**, the subtractor **102** supplies at the output, an image of a difference between the voltage  $V_{out}$  and the reference voltage  $V_{ref}$  which is supplied at the input of a proportional, integral (PI) or proportional, integral, derivative (PID) corrector **104**, or another type of corrector which delivers a control signal.

The signal is then supplied to an analog-to-digital converter **106** which converts the control signal into a digital signal the bits of which address each switch **82-i**.

For example, in one embodiment, the corrector **104** supplies a DC voltage image of the difference between the voltage  $V_{out}$  and the voltage  $V_{ref}$ . The DC voltage value is converted into a digital value by the converter **106**, e.g. coded over 3 bits. Each bit controls one of the switches **82-1**, **82-2**, **82-3**, the least significant bit controlling the switch connected to the lowest capacitance, and so on.

FIG. **4** is a partial, schematic representation of another embodiment of the invention. The inverter **10** is not shown, and the impedance matching unit has an architecture similar to the architecture described with reference to FIG. **3**. The rectifier unit **18** is simplified with respect to same described with reference to FIG. **3**.

In such embodiment, the capacitive circuit **14** includes P capacitors, and associated switches **82-1** to **82-P**.

In said embodiment, the control module **16** is a digital-control electronic module, e.g. a microcontroller, including an analogue-to-digital converter **108** which receives at the input thereof the output voltage  $V_{out}$ , which same converts into a digital value.

The digital-control electronic module is either integrated into the electrical energy converter or external to the electrical energy converter.

The digital-control electronic module **16** further includes a subtractor module **110**, which performs a subtraction between the digitized voltage value and the voltage setpoint value  $V_{ref}$ .

The difference DIFF between the two values is supplied at the input of a corrector **112**, e.g. a PID corrector, which supplies at the output, the control voltage values of each of the switches **82-1** to **82-P**.

Since the value given by the module **112** is a digital value, which is coded over P bits, each bit controls one of the switches, the least significant bit controlling the switch connected to the lowest value capacitor, and so on.

Alternatively, another output electrical parameter, e.g. the output current or the output power, and a setpoint value of said electrical parameter, are supplied to the digital-control electronic module.

FIG. **5** is a graph illustrating the output voltage  $V_{out}$  as a function of time, obtained as a function of the connections/disconnections of the capacitors of the capacitive circuit shown in FIG. **3**, via the closing/opening of the associated switches.

The graph shown in FIG. **5** is obtained by simulating connection/disconnection over time, as indicated above the x-axis.

During a first period T1, the switches are open.

During a second period T2, the first capacitor of capacitance  $Cvar\_1$  is connected in the capacitive circuit, the capacitance of the capacitive circuit being equal to  $Cvar\_1$ .

During a third period T3, the first capacitor of capacitance  $Cvar\_1$  is disconnected and the second capacitor of capacitance  $Cvar\_2$  is connected in the capacitive circuit, the capacitance of the capacitive circuit being equal to  $Cvar\_2$ .

During a fourth period T4, the first capacitor of capacitance  $Cvar\_1$  and the second capacitor of capacitance  $Cvar\_2$  are connected in the capacitive circuit, the capacitance of the capacitive circuit being equal to  $Cvar\_1 + Cvar\_2$ .

During a fifth period T5, the first capacitor of capacitance  $Cvar\_1$  and the second capacitor of capacitance  $Cvar\_2$  are disconnected and the third capacitor of capacitance  $Cvar\_3$  is connected in the capacitive circuit, the capacitance of the capacitive circuit being equal to  $Cvar\_3$ .

During a sixth period T6, the first capacitor of capacitance  $Cvar\_1$  and the third capacitor of capacitance  $Cvar\_3$  are connected in the capacitive circuit, the second capacitor of capacitance  $Cvar\_2$  being disconnected, the capacitance of the capacitive circuit is equal to  $Cvar\_1 + Cvar\_3$ .

During a seventh period T7, the first capacitor of capacitance  $Cvar\_1$  is disconnected and the second capacitor of capacitance  $Cvar\_2$  and the third capacitor of capacitance  $Cvar\_3$  are connected in the capacitive circuit, the capacitance of the capacitive circuit being equal to  $Cvar\_2 + Cvar\_3$ .

During an eighth period T8, the first, the second and the third capacitors are connected, the total capacitance being equal to  $Cvar\_1 + Cvar\_2 + Cvar\_3$ .

The eight successive periods correspond to steps of increasing output voltage values, ranging in the present example from 14.9 V to 25.7 V, i.e. a variation of 10.8 V.

In such example, the initial capacitance  $Cvar\_1 = C = 120$  pF,  $Cvar\_2 = 2C = 240$  pF and  $Cvar\_3 = 4C = 480$  pF.

The successive steps correspond to variable capacitance values  $Cvar$  ranging from 0 pF for the first period T1 to 840 pF during the eighth period T8, in increments of 120 pF per period, i.e. 120 pF for the second period, 240 pF for the third period etc.

Such embodiment of the invention is particularly advantageous, since the number of capacitors can be modulated and can be used for obtaining a variation by steps which can also be modulated.



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Advantageously, to obtain a fine granularity in the variation of the output voltage values, the capacitance value  $C$  (initial capacitance) is a small value, e.g. on the order of 5 pF to 120 pF.

Thus, in the embodiment described, the variable capacitances of the capacitors of the capacitive circuit are: 0,  $C$ ,  $2C$ ,  $4C$ ,  $8C$ , . . .  $2^{P-1}C$ , which can be used for obtaining values of  $C_{var}$  ranging from 0 to  $C_{var\_max}=(2^P-1)C$  in increments of  $C$ .

For example, in an application case, a specification defining a regulation range of the output voltage, between a minimum voltage and a maximum voltage.

The minimum voltage is used for computing the capacitance of the capacitor 68, and the maximum voltage indicates the capacitance  $C_{var\_max}$ , equal to the sum of all the capacitances of the capacitors of the capacitive circuit. In this way it is possible to choose the initial capacitance  $C$  and/or the number of capacitors.

The invention has been described hereinabove in an embodiment in which the capacitive circuit with variable capacitance is made by the parallel connection of a plurality of capacitors.

In variants, the capacitive circuit includes other types of capacitive components with controllable variable capacitance. E.g., the capacitive circuit includes a variable capacitor (or varicap) with a capacitance ranging from 100 pF to 200 pF, which allows for a continuous variation of the output voltage, and more generally of the chosen output electrical parameter, over the achievable regulation range depending on the capacitance variation range.

According to another embodiment, the capacitive circuit includes one or a plurality of adjustable MEMS (Micro Electro Mechanical System) capacitors.

The converter of the embodiment described in detail includes an L-piezo inverter and a class E rectifier.

Nevertheless, it is clear for a person skilled in the art that the invention applies with other inverter topologies, e.g. class E inverters, class Phi2 inverters.

Similarly, the invention applies with other rectifier topologies, e.g. class DE rectifiers.

According to another alternative, the invention also applies in DC-AC converters, for supplying an alternative load without rectification. In such case, the regulated electrical parameter is the amplitude of the output voltage, or the output current or power of the converter.

Advantageously, the invention finds application in many applications requiring a regulated output voltage, or a regulated output current or a regulated output power.

For example, the invention finds application in systems for supplying electrical power to electronic circuits, from a battery or a power bus.

The invention claimed is:

1. An electric power converter including an inverter for obtaining an alternative electrical energy from a source of DC electric power, said inverter comprising a switch including first and second conduction terminals for receiving an alternative voltage, said electrical energy converter being suitable for supplying an output electrical energy to a load

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having a load impedance, said converter comprising a capacitive circuit with variable and controllable capacitance, connected between the inverter and the load, the control of a change in said capacitance being used for obtaining a change in an output electrical parameter of the converter.

2. The converter according to claim 1, wherein said output parameter is an output voltage or current or power of the converter.

3. The converter according to claim 1, comprising an impedance matching unit configured for matching an output impedance of said inverter with the load impedance, said capacitive circuit with variable capacitance being connected between the impedance matching unit and the load to be supplied.

4. The converter according to claim 3, further comprising a rectifier unit for obtaining a DC electrical energy from a source of AC electrical energy, said rectifier unit being connected between the capacitive circuit with variable capacitance and the load to be supplied.

5. The converter according to claim 1, further comprising a regulator unit configured for switching the switch when the voltage between said first and second conduction terminals of said switch is substantially zero.

6. The converter according to claim 1, wherein the capacitive circuit comprises a plurality of capacitors arranged in parallel, each capacitor being connected in series with an associated switch, said capacitor being connected in the capacitive circuit when the associated switch is in the closed position, said capacitor being disconnected from the capacitive circuit when the associated switch is in the open position, the variable capacitance of said capacitive circuit being equal, at a given instant, to the sum of the capacitances of the capacitors connected in the capacitive circuit at said given instant.

7. The converter according to claim 6, wherein one of said capacitors has an initial capacitance, the other capacitors each having a capacitance which is a multiple of said initial capacitance.

8. A system for converting electrical energy including an electrical energy converter according to claim 1 and a control module configured for receiving as input, a setpoint value of said output electrical parameter of the converter and for controlling the variable capacitance of said capacitive circuit as a function of said setpoint value.

9. The system for converting electrical energy according to claim 8 wherein said control module comprises a subtractor configured for receiving, at a first input, a value of said output electrical parameter of the converter and for receiving, at a second input, the setpoint value of said electrical parameter, said subtractor being configured for computing a difference between the value of the output electrical parameter of the converter and the setpoint value.

10. The system for converting electrical energy according to claim 9, wherein said control module further comprises a conversion module configured for converting the calculated difference into a control signal of the capacitive circuit.

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